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DIRECT CAPTURE AT LOW ENERGIES

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Abstract: The importance of direct capture for (n,γ) -reactions on intermediate- and heavy-mass target nuclei occurring in the s- and r-process is investigated. It is shown that the direct mechanism is non-negligible for magic and neutron rich target nuclei. For some double magic and neutron rich nuclei in the r-process direct capture is even the dominant reaction mechanism.

1 Introduction

The reaction mechanism of radiative capture can be classified by two extremes: the reaction proceeds as a multi-step process (compound-nucleus reaction: CN) or in a single step (Direct Capture: DC). In the last years it was realized that for light nuclei DC is often the dominating reaction mechanism in astrophysically relevant nuclear processes. The DC-method together with the folding procedure has been applied successfully by our group to radiative capture in primordial nucleosynthesis ($^2\text{H}(\alpha,\gamma)^6\text{Li}$ [1], $^3\text{H}(\alpha,\gamma)^7\text{Li}$ [2], $^7\text{Li}(\text{n},\gamma)^8\text{Li}$ [3]), the pp-chain ($^3\text{He}(\alpha,\gamma)^7\text{Be}$ [2], $^7\text{Be}(\text{p},\gamma)^8\text{B}$ [3]), CNO-cycle ($^{13}\text{N}(\text{p},\gamma)^{14}\text{O}$ [4]) and helium burning ($^8\text{Be}(\alpha,\gamma)^{12}\text{C}$ [5]).

In this work we want to investigate the importance of the DC mechanism for (n, γ)-reactions on intermediate- and heavy-mass target nuclei occurring in the s- and r-process. In Section 2 we introduce the DC formalism and the folding procedure. In Section 3 the relativistic mean field theory (RMFT) and its application to neutron rich nuclei will be discussed. Finally in Section 4 we compare the influence of DC to radiative capture cross sections in the s- and r-process.

2 Direct capture and folding procedure

The theoretical cross section σ^{th} is obtained from the DC cross section σ^{DC} given by [6], [7], [2]

$$\sigma^{\text{th}} = \sum_i C_i^2 S_i \sigma_i^{\text{DC}} \quad . \quad (1)$$

The sum extends over all possible final states (ground state and excited states) in the final nuclei. The isospin Clebsch-Gordan coefficients and spectroscopic factors are C_i and S_i , respectively. The DC cross sections σ_i^{DC} are essentially determined by the overlap of the scattering wave function in the entrance channel, the bound-state wave function in the exit channel and the multipole transition-operator. For the computation of the DC cross section we used the direct-capture code TEDCA [8].

The folding procedure is used for calculating the nucleon-nucleus potentials in order to describe the elastic scattering data and the bound states. This method was already applied successfully in describing many nucleon-nucleus systems. In the folding approach the nuclear density ρ_A is derived from experimental charge distributions [11] and folded with an energy and density dependent NN interaction v_{eff} [9]:

$$V(R) = \lambda V_{\text{F}}(R) = \lambda \int \rho_A(\vec{r}) v_{\text{eff}}(E, \rho_A, |\vec{R} - \vec{r}|) d\vec{r} \quad . \quad (2)$$

with \vec{R} being the separation of the centers of mass of the two colliding nuclei. The normalization factor λ is adjusted to elastic scattering data and to bound- and resonant-state energies. The potential obtained in this way ensures the correct behavior of the wave functions in the nuclear exterior. At the low energies considered

in nucleosynthesis the imaginary parts of the optical potentials are small. The folding potentials of Eq. 2 were determined with the help of the computer code DFOLD [10].

3 Application of RMFT to neutron rich nuclei

The RMFT describes the nucleus as a system of Dirac nucleons interacting via various meson fields. In the last few years this theory has turned out to be a very successful tool for the description of many nuclear properties (for example binding energies and charge radii for stable isotopes) [12]. The RMFT is built upon two main approximations: the mean-field approximation and the no-sea approximation. The mean-field approximation removes all quantum fluctuations of the meson fields and uses their expectation values. This approach cuts down all many body effects because the nucleons move as independent particles in the meson fields. The no-sea approach neglects all contributions from antiparticles. Only negative energy states are taken into account. One great advantage of the RMFT is that the spin-orbit interaction is described in a proper way without any additional parameters.

The theory starts with an effective interaction of Dirac nucleons with mesons and the electromagnetic field. We work with the $(\sigma\omega\rho)$ -model [13]. The σ -meson mediates the medium range attraction between the nucleons. The isoscalar vector mesons ω cause a short-range repulsion. The contribution of the ρ -mesons is important for neutron- and proton-rich nuclei. There are six parameters which are usually obtained by fits to finite nuclear properties: each coupling constant of the meson fields with the nucleons g_σ , g_ω and g_ρ , the constants of the nonlinear σ -potential g_2 , g_3 , and the mass of the σ -meson. The other meson masses are given empirically.

In our calculations we have used the parameter sets NLSH [14], [15] and NL1 [16]. The parameter set NL1 is fitted to the ground state binding energies and charge radii of spherical nuclei. This set overpredicts the neutron radii of neutron rich nuclei. The set NLSH has been fitted not only to binding energies and charge radii, but also to the neutron radii of several spherical nuclei. The binding energies of Sn-isotopes as a function of mass number show a kink at $A = 132$ (upper part of Fig. 1) signifying the shell effect at the magic neutron number $N = 82$. The neutron-skin thickness of the Sn-isotopes also show this kink by about $0.25(N - Z)/A$ (lower part of Fig. 2). The values for the neutron-skin thickness calculated with the parameter set NLSH are about 20 % less than the values determined with NL1. The results of NLSH for the binding energies and neutron-skin thickness for stable neutron rich nuclei are comparable to the experimental data (see Fig. 1). For nuclei in the r-process (e.g. ^{132}Sn – ^{138}Sn) the neutron skin has a value of about 0.5 fm.

With the RMFT we also can determine the proton and neutron density distribution for the Sn-isotopes. We found acceptable agreement between the calculated proton-density distributions obtained from RMFT for the stable Sn-isotopes ^{112}Sn – ^{124}Sn with the experimental data [11].

Figure 1: Upper part: Binding energies of Sn-isotopes calculated with RMFT using the parameter set NLSH. Lower part: Neutron-skin thickness of Sn-isotopes calculated with RMFT using the parameter sets NL1 (broken curve) and NLSH (solid curve) compared with experimental data [17].

Table 1. DC-calculations of radiative capture cross sections on neutron-magic target nuclei compared with the experimental data.

Reaction	$\langle\sigma_{\text{DC}}\rangle(25 \text{ keV})$ [mb]	$\langle\sigma_{\text{EXP}}\rangle(25 \text{ keV})$ [mb]
$^{48}\text{Ca}(n,\gamma)^{49}\text{Ca}$	0.96	1.03 ± 0.09 [23]
$^{86}\text{Kr}(n,\gamma)^{87}\text{Kr}$	0.09	3.54 ± 0.25 [24]
$^{88}\text{Sr}(n,\gamma)^{89}\text{Sr}$	0.26	7.0 [25]
$^{136}\text{Xe}(n,\gamma)^{137}\text{Xe}$	0.16	1.05 ± 0.09 [24]
$^{138}\text{Ba}(n,\gamma)^{139}\text{Ba}$	0.44	4.46 ± 0.21 [26]
$^{208}\text{Pb}(n,\gamma)^{209}\text{Pb}$	0.13	0.31 [25]

4 Direct capture for intermediate- and heavy-mass nuclei

In this section we want to investigate the importance of DC for intermediate- and heavy-mass target nuclei in the s- and r-process. The DC will be large compared with the CN contribution, if the level density of the compound nucleus is low, because then there will be only a few states in the compound nucleus, which can be excited in the reaction. This is true for example for the radiative capture reactions on light nuclei cited in the introduction. For intermediate- and heavy-mass nuclei this is also the case if the Q-value of the reaction *as well as* the projectile energy are small.

For radiative capture on intermediate- and heavy-mass target nuclei induced by charged particles in astrophysical scenarios the projectile energy is so large that DC can be neglected. For instance, the DC-contribution of $^{144}\text{Sm}(\alpha,\gamma)^{148}\text{Gd}$ is at least 5 orders of magnitudes lower than the CN-contribution [19]. However, a low level density of the compound nucleus can occur for radiative capture of neutrons on neutron-magic and/or neutron rich target nuclei in the s- or r-process.

In Table 1 we show the results of the DC-contributions of (n, γ)-reactions for some neutron-magic target nuclei with $N = 28$ [20], $N = 50, 82$ [21] and $N = 126$ [22] occurring in the s-process. The DC-calculations were performed using the folding procedure for the optical and bound-state potentials as presented in Sect. 2. The average cross sections $\langle\sigma\rangle$ at $kT = 25 \text{ keV}$ are compared to the experimental data. As can be seen the DC gives non-negligible contributions to the total cross sections. A special case is neutron capture on the double magic, neutron rich nucleus ^{48}Ca , where up to about 1 MeV no compound-nucleus levels exist, which can be excited. Therefore, for this reaction the cross section is almost given entirely through DC.

As an example for neutron rich nuclei we investigated the radiative capture on Sn-isotopes up to the r-process path. The cross sections for such (n, γ)-reactions are needed for the description of the freeze-out in the r-process [27]. Since in this case no experimental data is available we compared the DC- with the CN-calculations as obtained from the statistical Hauser-Feshbach (HF) method. In order to make

Table 2. DC- and HF-calculations of radiative capture cross sections on neutron rich nuclei.

Reaction	Q-value [MeV]	$\langle\sigma_{\text{DC}}\rangle(30 \text{ keV}) [\mu\text{b}]$	$\langle\sigma_{\text{HF}}\rangle(30 \text{ keV}) [\mu\text{b}]$
$^{132}\text{Sn}(n,\gamma)^{133}\text{Sn}$	2.581	220.7	116.4
$^{134}\text{Sn}(n,\gamma)^{135}\text{Sn}$	1.871	132.4	32.5
$^{136}\text{Sn}(n,\gamma)^{137}\text{Sn}$	1.611	101.0	18.5
$^{138}\text{Sn}(n,\gamma)^{139}\text{Sn}$	1.230	60.4	8.4

a meaningful comparison between the DC- and CN-reaction mechanism, we used the same masses, Q-values, spin assignments and excitation energies and optical potentials in both calculations.

The densities necessary for the determination of neutron-nucleus folding potentials (Eq. 2) involving unstable nuclei cannot be taken any more from experimental data. We obtained them from the RMFT using the parameter set NLSH as described in Section 3. The strengths of the folding potentials were adjusted to reproduce the same value of the volume integral of 425 MeV fm^3 as determined from the experimental elastic scattering data on the stable Sn-isotopes [28], [29]. In order to obtain experimentally unknown masses and Q-values a microscopic-macroscopic mass formula based on the FRDM was used [30]. The spin assignments and the excitation energies of the ground and low-excited states of the odd residual nuclei ^{133}Sn – ^{139}Sn have been taken from [31]. For the neutron spectroscopic factors necessary for the DC-calculation a value of unity was assumed. This assumption should be reasonable for the neutron rich Sn-isotopes involved in the r-process.

The statistical-model calculations were performed with the code SMOKER [32]. Above the highest known state a level density description based on the backshifted Fermi gas [33] is employed, with parameters as given in [34]. The imaginary parts of the optical potential necessary for the HF-calculations were taken from [35].

In Table 2 we show the results of the DC- compared to the HF-calculations for the averaged cross section at 30 keV on the even target nuclei ^{132}Sn – ^{138}Sn . As can be seen from this table both cross sections decrease when going to lower Q-values. However, the HF-cross section decreases much faster due to the lower level density of the compound nucleus. For the neutron-capture on ^{138}Sn the DC is about 7 times as high as the CN contribution as obtained with the HF-method.

Summarizing, we showed that DC is not only important for radiative capture on light nuclei, but is also non-negligible for magic and neutron rich target nuclei. For some double magic and neutron rich nuclei in the r-process DC is even the dominant reaction mechanism.

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